

Bismuth-Silicon and Bismuth-Polyurethane Composite Shields for Breast Protection in Chest Computed Tomography Examinations

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Abstract

The article aims at constructing protective composite shields for breasts in chest computed tomography and investigating the effects of applying these new bismuth composites on dose and image quality. Polyurethane and silicon with 5% of bismuth were fabricated as a protective shield. At first, their efficiency in attenuating the X-ray beam was investigated by calculating the total attenuation coefficients at diagnostic energy range. Then, a physical chest phantom was scanned without and with these shields at tube voltage of 120 kVp, and image parameters together with dose values were studied. The results showed that these two shields have great effects on attenuating the X-ray beam, especially for lower energies (<40 kV), and in average, the attenuation coefficients of bismuth-polyurethane composite are higher in this energy range. The maximum relative differences between the average Hounsfield units (HUs) and noises of images without and with shield for both composites in 13 regions of interest were 4.5% and 15.7%, respectively. Moreover, primary investigation confirmed the ability of both shields (especially polyurethane-bismuth composite) in dose reduction. Comparing these two composites regarding the amount of dose reduction, the changes in HU and noise, and attenuation coefficients in diagnostic energy range, it seems that polyurethane composite is more useful for dose reduction, especially for higher tube voltages.

Keywords: Bismuth composites, breast shielding, computed tomography, dose reduction, Hounsfield unit, noise

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INTRODUCTION

Chest computed tomography (CT) scan is used as a valuable and precise diagnostic imaging tool for the noninvasive assessment of lungs, heart, and mediastinum diseases. The major disadvantage of this imaging is the radiation exposure to superficial organs (i.e., breasts in chest scan), which are not usually the target of examinations. The risk of cancer increases linearly with increasing dose, with higher risks for females,^[1] and exposures to young girls around the age of menarche and breast bud carry a high risk.

A common method for dose reduction during CT examinations is the use of shielding to protect superficial organs.^[2,3] Shields could remove the lower energies in the X-ray spectrum, and materials with higher attenuation coefficients in diagnostic energy range eliminate the lower energies with smaller required thickness and therefore reduce the image artifacts.^[4] Numerous investigations have reported the use of high atomic number (Z)

shielding materials such as lead and bismuth to attenuate X-rays and γ -rays.^[5,6]

Despite the advantages of using protective shields in decreasing the dose values, concerns are being raised regarding their impacts on image quality.^[7] Some statements are discouraging about applying shields,^[8] while in some reports, it was stated that using this technique reduces the surface dose to patients with no appreciable loss in diagnostic quality.^[9,10]

As reported in the literature, bismuth is an appropriate in-plane shield for protecting superficial organs. The study of Kim *et al.*^[11] on the amount of breast dose reduction using bismuth

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shielding indicated that shield enabled a 16%–37.5% dose reduction in the breast, while it increased CT images' noise up to 40%. Tappouni and Mathers^[12] assessed the effects of bismuth breast shield on dose and image quality. They showed that breast shield decreased dose to the anterior chest by 38% and caused a reduction in noise by a factor of 1.86 in the anterior compared to posterior regions.

It should be mentioned that besides the effectiveness of a protective shield on dose reduction and not degrading the image quality, additional factors such as conformability, cost-effectiveness, weight factor, toxicity, and durability are important in selecting shields. In the past decades, several investigations have reported application of nano- and micro-polymer composite materials to attenuate high energy radiation. Because of their favorable properties, these materials have great potential to be used as radiation protective shields.^[13]

Based on the mentioned points, for the first time, two different homemade composites of polyurethane and silicon with 5% of bismuth were constructed and their impacts on image quality and dose were investigated. To verify their effects on dose reduction due to the presence of bismuth composite shields, thermoluminescence dosimeters (TLDs) were inserted in breasts and dose values were measured without and with both shields.

MATERIALS AND METHODS

Appropriate shield

In this study, to construct bismuth composites, silicon and polyurethane were used as matrices for bismuth particles. Bismuth powder (metal beads with maximum sizes of 150 μm provided from Merck Group) was poured gently by a pipette on a silicon or polyurethane flat surface with a thickness of 1.1 mm and an area of 30 cm \times 40 cm. These shields were left in the oven at 60°C and humidity of 90% for 10–15 days. This method gently and continuously dries the composite mixtures with no air bubbles. On exiting the oven, they were left for 1 day at room temperature (25°C) to adapt with the normal situations, and then, they were used for the experiments. To compare the shields, attenuation coefficient of each element of both bismuth composites was obtained from XCOM program,^[14] and then, total mass attenuation coefficients of composites in CT energy range (<120 kVp) were calculated by compiling a FORTRAN program.

Chest physical phantom

A physical chest phantom of a female was designed and built based on the recommendation of ICRP publication 23,^[15] ICRU report 48, and also the available anatomical data of lung and breasts in Tabriz University of Medical Sciences. The initial plan of the chest phantom was drawn using AutoCAD 2012. Based on the plan and by a waterjet cutter, phantom was cut into slices with thickness of 1 cm. Breasts and chest were made of polyethylene, and the lung was fabricated by cork. Two different breasts sizes were considered for female phantom to mimic different women physically and radiographically.^[16]

Figure 1 displays the designed physical female chest phantom with two different breasts sizes.

Computed tomography examinations

The female phantom was placed in a supine posture at the isocenter of a Siemens Somatom Sensation 16 scanner. The conventional chest scanning parameters for adults considered by the machine automatically (tube voltage of 120 kVp, tube current of 80 mA, slice thickness of 10 mm, pitch of 1.3, and pixel size of 2 mm \times 2 mm) were used for phantom imaging. The shields were placed on foam with thickness of 1 cm, and then, they were made to cover the anterior surface of the breasts. To avoid increasing the scan parameters after placing shields were placed after acquiring the CT topogram.

Image-quality analysis

To investigate the effects of shield on image quality, CT scans were performed without and with shields and the image quality was evaluated. Bismuth-silicon and bismuth-polyurethane composites were placed on small breast and big breast, respectively. The quantitative assessments of image quality include determining the differences between HU and noise of shielded and unshielded images. For this purpose, five circular regions of interest (ROIs) in the trunk and four ROIs in each breast, with area of 1.9 cm², were selected to measure both the average HU and the standard deviation (SD) in each region. The measures of SD can be used as a quantitative assess of noise within CT images, and collecting the average HU will check for variations caused by the presence of shields.^[17] ROIs were selected in the trunk and breast of phantom (in anterior, in lateral, in middle, and in posterior) on consecutive slices. Moreover, statistical analysis was performed using Statistical Package for the Social Sciences (SPSS) software developed by IBM Corporation and $P < 0.05$ was considered as the significance of the results.

Dosimetric evaluation

An initial assessment for the effects of these two composites on dose reduction was done using calibrated, energy-specific LiF: Mg, Cu, P (GR-200) TLDs (Hangzhou Freqcontrol Electronic Technology Ltd., China). They were placed inside the breasts



Figure 1: Physical female phantom

of the phantom for irradiation without and with the presence of shield. Readout of the TLDs was done in a 7103 model Raman Security Development Co. TLD reader^[18] during the temperature of 240°C for 10–20 s.

RESULTS

In Figure 2, the radiographic images of bismuth-silicon and bismuth-polyurethane composites at tube voltage of 40 kV are represented. The bismuth beads are noticed on the surface of composites. For these two composites, Figure 3 displays the total attenuation coefficients in cm^{-1} .^[14] From figure, although two composites are similar in low energies, the attenuating property of polyurethane is more than silicon in higher energies. Considering the figure, for scans performed at lower tube voltages (i.e., 80 or 100 kVp instead of 120 kVp), these shields have more effects on beam attenuation and consequently their dose reduction rate might increase.

Figure 4 displays the ROIs selected in all five slices of CT images. Each ROI identifies with a number. For the ROI located in the middle of chest, the circular area, mean HU, and standard deviation were measured. For these selected ROIs, the average value of HU, and noise without and with the presence of bismuth composite shields on the surface of phantom are tabulated in Table 1. From Table 1, the HU values increased up to 4.5% and 1.8% for images shielded by polyurethane and silicon composites, respectively, while the increase in noises were 15.7% and 15.02%, respectively. The *P* values of the differences between HUs without and with shields were not statistically significant ($P > 0.05$).

The outcomes of dosimetric measurements with TLDs using two shields showed 9.57% and 37.6%, dose reduction by

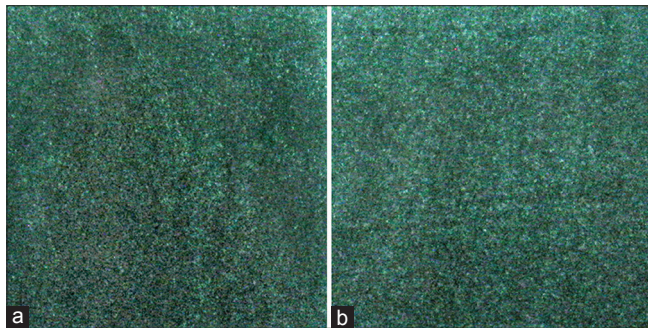


Figure 2: The radiographic images of (a) bismuth-silicon composite and (b) bismuth-polyurethane composite at tube voltage of 40 kV and tube loading of 1.6 mAs. The bismuth beads are observed as bright spots

bismuth-silicon and bismuth-polyurethane composites, respectively.

DISCUSSION

Despite the advantages of CT scan in diagnostic procedures, its increasing and frequent use raises concern about the radiation dose. It was reported that the value of effective dose, as a protection quantity, in chest CT scan (5.4 mSv) is almost 54 and 68 times more than that in mammography (0.1 mSv) and chest radiography (0.08 mSv), respectively.^[19] Therefore, it seems that reducing radiation dose, especially for superficial radiosensitive organs, which are not usually the target of imaging, is important.^[17] Hitherto, the effects of shielding superficial organs by high-attenuating materials (e.g., bismuth) on radiation dose reduction are reported frequently by various investigators.^[17,18,20-24] Geleijns *et al.* were concerned about the inclusion of breast shields in CT scan range, which may cause streak artifacts and diminish image quality,^[7] and also the amount of unavoidable internally scattered radiation.^[25] Some investigators believed that optimizing scan protocol may have a greater effect on patient radiation dose than the use of patient shields.^[20,26]

In addition, it was reported that polymer-based shielding materials are lightweight and conformable, and they can be designed to include nontoxic, high *Z* materials that provide effective X-ray protection.^[13] In Table 2, some of the investigations used conventional breast shields were tabulated.

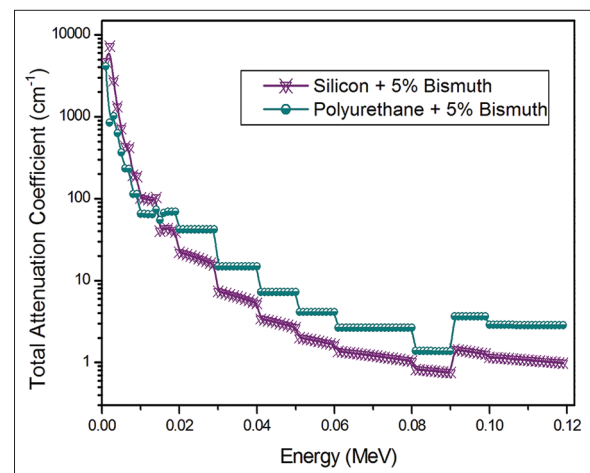


Figure 3: Total attenuation coefficients of two bismuth composites in diagnostic energy range

Table 1: Average Hounsfield unit and noise in the computed tomography images without and with shields of bismuth-polyurethane and bismuth-silicon composites

Location	Without shield				Bismuth-silicon composite				Without shield				Bismuth-polyurethane composite			
	9	10	11	12	9	10	11	12	5	6	7	8	5	6	7	8
Average HU	-62.33	-64.00	-65.00	-67.00	-61.91	-62.86	-64.16	-66.5	-61.75	-64.86	-64.00	-67.13	-59.75	-62.57	-61.13	-64.56
Noise	2.33	5.12	4.50	8.12	2.68	5.48	4.98	8.88	2.10	3.13	3.61	5.59	2.43	3.55	4.00	6.31

HU: Hounsfield unit

Table 2: Some studies conducted on the effects of shielding breast by bismuth layer on image quality in chest computed tomography scans

Authors	Method	Shield	Results
Geleijns <i>et al.</i> ^[7]	A RANDO phantom was scanned by a MDCT scanner at tube voltage of 120 kVp and tube loading of 100 mAs	Bismuth shield (F and L Medical Products Co., USA)	Image noise was increased by 5.5% in chest scan
Coursey <i>et al.</i> ^[21]	Atom pediatric 5-year-old phantom (model 705-D, CIRS) was scanned by a MDCT scanner	Bismuth shield (F and L Medical Products Co., USA)	Mean noise was not significantly different with the addition of the breast shield
Kalra <i>et al.</i> ^[22]	An anthropomorphic chest phantom (GmbH, Germany) was scanned by a MDCT scanner	Bismuth shield (F and L Medical Products Co., USA)	Increase in HU and noise (53.5%) was noted directly below the shield
Catuzzo <i>et al.</i> ^[23]	RANDO phantom was scanned by two different MDCT scanners	4 layers of 0.0085 g/cm ² bismuth latex	There was no significant difference in noise
Wang <i>et al.</i> ^[24]	An anthropomorphic chest phantom (GmbH, Germany) was scanned by a MDCT scanner	A breast shield made of bismuth-impregnated latex	Shielding led to a substantial increase in HU by 10-20 HU
Einstein <i>et al.</i> ^[27]	Atom phantom (model 701; CIRS) was scanned by a MDCT scanner	Bismuth shield (F and L Medical Products Co., USA)	HU was decreased by 14.6 HU
Servaes and Zhu ^[28]	Atom pediatric 5-year-old phantom (model 705-D, CIRS) was scanned by a MDCT scanner	Bismuth shield (F and L Medical Products Co., USA)	Noise level increased by 4-6 HU
Alonso <i>et al.</i> ^[29]	A RANDO female phantom was scanned at tube voltage of 120 kVp and tube current of 150 mA by a MDCT scanner	1 mm thick Bismuth breast shield	Image noise increased (there was no quantitative assessment)

MDCT: Multiple detector computed tomography, HU: Hounsfield unit, CIRS: Computerized imaging reference systems

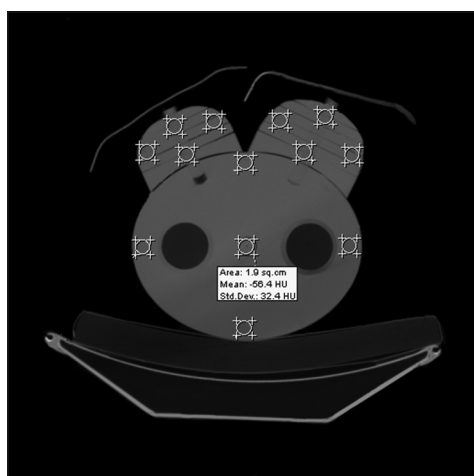


Figure 4: Thirteen regions of interest selected for image analysis. Bismuth-silicon and bismuth-polyurethane composites were placed on small breast and big breast, respectively. The average Hounsfield unit value and noise were determined for the marked places with an area of 1.9 cm²

According to the outcomes, the relative differences between the average HUs of images without and with shield in 13 different ROIs were <4.5% for both shields. In addition, the maximum increase in noise was observed directly below the shields, which was 15.7% for polyurethane composite shield and 15.02% for silicon composite [Table 1]. Given Table 2, most of the studies reported an increase in HU and noise. The results of this study confirm this as expected. It could be said that applying shields affects the values of HU because the effective energy of X-ray is changed and HU is directly dependent on energy. In addition, the increase in image noise is likely related to the beam hardening and scattering associated with the presence of shield.^[22]

Considering the assessments of image quality, it seems that these two bismuth composites have no significant

impact on HU and noise in the inner body and the maximum changes in these values relate to the breast, which locates directly below the shield. As long as the breast is not the target of imaging, these shields help reducing the high level of breast dose absorbed as the byproduct of its location. Comparing these two composites, the changes in HU and noise in bismuth-polyurethane composite are more than bismuth-silicon composite, but the differences are not statistically significant ($P > 0.05$). On the other hand, considering the amount of dose reduction, bismuth-polyurethane composite is more useful in dose reduction for diagnostic procedures, especially for higher tube voltages, which is expected from its attenuation property.

CONCLUSIONS

Given the advantages of polymer composite over conventional materials for protective shields, two different bismuth composites were designed and fabricated. Polyurethane and silicon with 5% of bismuth were constructed as breast protective shield, and their effects on image quality and dose reduction in chest CT scan were investigated. According to the results, both composite shields reduce dose values and increase noises, which are most evident directly below the shield, but they do not cause distractions. However, breasts are not usually the target of CT imaging, so shields cannot interfere with diagnostic procedures.

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Conflicts of interest

There are no conflicts of interest.

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